Chemistry research in India: making progress, but not rapidly

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Against the backdrop of comments on chemistry research in India made in three recent reports prepared by Nature Index, Elsevier and Thomson Reuters, we have made a scientometric analysis of contributions from India in leading multidisciplinary chemistry journals over the 25-year period 1991–2015. We have compared India's performance with that of China as a benchmark. Overall, the number of chemistry papers from India increased steadily between 2007 and 2014. The three-year moving average of number of papers during the period grew at a compound annual growth rate of 8.9%, and the overall increase in papers was accompanied by a more than proportionate increase in the leading journals. Also, the average number of cites received by papers with at least one author from India in Angewandte Chemie International Edition (Angew. Chem. Int. Ed.) and Accounts of Chemical Research was higher than the world average. Despite its huge share of the world's population (~17%), India continues to be poorly represented in the top journals: the country's share of papers in the Journal of the American Chemical Society is 0.7% compared to 58.4% for USA, 7.6% for Germany and 5.1% for China, and its share in Angew. Chem. Int. Ed. is 1.2% compared to 28% for Germany, 25.3% for USA and 9.9% for China. This could be due to the fact that till recently Indian universities did not encourage mobility across disciplines. That only a small number of Indian researchers and institutions publish in leading journals is also a matter for concern. India accounts for only a small number of papers in the top one percentile of the most highly cited chemistry papers, whereas China leads the world. Only 2.3% of the 2234 papers published in 2014 that are in the top one percentile is from India compared to 38% from China.

Keywords: Chemistry research, international collaboration, multidisciplinary journals, scientometric analysis.

THIS article takes off from the brief but perceptive essay on chemistry in India by Arunan *et al.*[1]. We provide quantitative data to show that despite an increase in research output and international collaboration, chemistry research in India is still not in the big league.

We begin with what has been said in some recently released reports on the status of science in India and present some data we gathered from databases such as *Natureindex.com, SCImago,* and *Web of Science–Science Citation Index Expanded* (*WoS–SCIE*). Then we analyse contributions made from Indian laboratories in six general chemistry journals as well as the chemistry papers in *Nature*, *Science* and *Proceedings of the National Academy of Sciences, USA* and identify prominent institutions and individuals. We compare India's performance with that of a few other countries.

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Earlier studies

Nature Index report on India

According to a Nature Index report[2], chemistry is doing well in India and indeed it is the top performer. The report presents an analysis of primary research papers published in 68 top-quality journals selected by an international panel of experts, and shows that there has been a marked growth in research output despite 'stagnant funding for R&D as a percentage of GDP, red tape, government indifference and unfair appointments'. According to the report, India has done well particularly in chemistry, as reflected by papers published in a set of 14 chemistry journals and chemistry papers in four multidisciplinary journals (http://www.natureindex.com/faq#subjects). Of the 68 journals tracked by Nature Index, the top ten journals used by Indian scientists are all in

chemistry and physical sciences. Also, chemistry accounts for half of India's overall Nature Index output, reflecting the country's strong propensity towards the discipline. India currently occupies the eighth position globally in chemistry (as against 13th in all of science) with weighted fractional count (WFC) of 516.8 papers in 2015–2016 (http://www.natureindex.com/). Nature Index has selected chemistry research in India as a rising star[3]. To see India's performance in perspective, South Korea is ahead of India with a chemistry-specific WFC of 590.40 (although its population is just about 3.8% that of India (www.worldmeters.info) and its nominal GDP less than 60% (Statisticstimes.com; IMF World Economic Outlook, April 2016)) for the same period and China is far ahead (WFC 4194.16). Both China and South Korea have been ahead in Nature Index ever since it started providing such rankings. India is catching up with South Korea in the number of papers. India's chemistry-specific WFC grew by 175 between 1 January 2012 and 31 May 2016 for a compound annual growth rate (CAGR) of 12.65% as against 15.5% for China and 1.3% for South Korea (as seen from Nature Index on 24 July 2016).

Chemistry accounts for more than a third of internationally co-authored papers published in the 68 journals tracked by Nature Index. The share of chemistry papers in which there was at least one author from India rose from 35.5% of all Indian papers in the journals tracked by Nature Index in 2012 (ref. 4) to 36.2% in 2015 (ref. 5). The corresponding figures for South Korea were 41% in 2012 and 40.5% in 2015, and for China 47.7% in 2012 and 53% for 2015.

SCImago

According to *SCImago* (http://www.scimagojr.com), Asia overtook USA in 1996 and Western Europe in 2004 in the number of papers published in chemistry. By 2014, the gap had widened. Of the 228,428 chemistry papers from the world as a whole, Asia had published 106,763 papers compared to 56,404 from Western Europe and 40,379 from North America. Apart from China, Japan, South Korea and India, Singapore and Taiwan also contribute to the Asian surge in chemistry. India's contribution to the literature of chemistry, according to *SCImago*, grew from 4,035 citable documents in 1996 to 6,664 in 2004 and 16,576 in 2014. In terms of percentage share of the world's literature of chemistry, India accounted for 3.88 in 1996, 4.59 in 2004 and 7.37 in 2014. In the Asiatic region, India's share declined from 16.12% in 1996 to 14.35% in 2004, but recovered to 15.76% in 2014. India's share in the Asiatic region remained virtually stagnant largely because of the huge strides made by China.

There were 232,304 papers in the 857 journals *SCImago* had indexed in 2015 under the category 'Chemistry', as seen on 17 June 2016. India was ranked third with 16,159 papers, next only to China (63,193 papers) and the United States (35,610 papers). Papers from India were classified into analytical chemistry (1,635), chemistry – miscellaneous (8,166), electrochemistry (491), inorganic chemistry (1,432), organic chemistry (3,402), physical and theoretical chemistry (3,096) and spectroscopy (1,376). Numbers assigned to subfields add up to far more than the total for all of chemistry, the field classification is based on journals, and as journals may be assigned to more than one field.

Elsevier report to DST

According to a report prepared by Elsevier for the Department of Science and Technology, New Delhi[6], there were 64,492 active chemistry researchers – 17.6% of all the 366,445 researchers – affiliated with Indian institutions during 2009–2013 (see p. 93 of the report). [According to an earlier version of the report[7], dated December 2015, the number was 8,367 active chemistry researchers out of a total of 82,501 (10.1%). Arunan *et al.*[1] had given a rough estimate of 10,000 chemistry researchers.] During 2009–2014, there were 81,080 chemistry papers from India, accounting for 6.9% of all chemistry papers published, higher than the share of Indian papers in all other areas. The number of papers published in chemistry from India during 2009–2013 grew at a CAGR of 7.9%, in contrast to 9.9% for China and 4.4% for the world.

The institutions which published the largest number of chemistry papers were the Indian Institute of Science, Bengaluru (2,562); Indian Institute of Technology, Kharagpur (1,677); Indian Association for the Cultivation of Science, Kolkata (1,598); Indian Institute of Technology Bombay, Mumbai (1,496); Jadavpur University, Kolkata (1,462); University of Delhi, Delhi (1,429).

There were 2,895 papers in all of science from India among the top 1% of the most highly cited papers during this period. Of these, 394 (or 13.6%) were chemistry papers. In other words, only 0.49% of all the 81,080 chemistry papers were among the top 1% of highly cited papers. Of the 16,999 papers from China, which were in the top 1% of highly cited papers of the world, 3,667 (or 21.6%) were in chemistry. In other words, 1.33% of the more than 276,000 chemistry papers from China were among the top 1% of highly cited papers.

There were 55,402 papers from India in the top 10% of highly cited papers during 2009–2013. Of these, 7,211 (or 13.02%) were in chemistry. In other words, 8.9% of all the chemistry papers from India during the period were among the top 10% of highly cited papers. Of the 282,498 papers from China, which were in the top 10% of highly cited papers, 37,937 (or 13.4%) were chemistry papers. In other words, 13.71% of all the chemistry papers from China were among the top 10% of highly cited papers.

In a few other fields, there were larger number of papers than in chemistry among both the top one percentile and

the top 10% of highly cited papers from India. For example, of the 2,895 papers in all of science from India among the top 1% of the most highly cited papers during this period, 949 (32.8% or 0.88% of 108,348 papers) were in engineering, 542 (18.7% or 0.70% of 77,310 papers) in computer science, 538 (18.6% or 0.49% of 110,367 papers) in medicine, and 527 (18.2% or 0.67% of 79,129 papers) in physics and astronomy. Of the 55,402 papers from India in the top 10% of highly cited papers, engineering (19,532; 35.3%), computer science (17,535; 31.7%), physics and astronomy (8343; 15.1%), and materials science (8172; 14.8%) were the top fields.

Thomson Reuters report to DST

According to a report prepared by Thomson Reuters for DST[8], chemistry research in India is growing rapidly. The number of chemistry papers published from India nearly doubled between 2005 and 2014. In the ten years from 2005 to 2014, Indian researchers have published 89,598 chemistry papers. India's share in all of science during 2014 was 4.05%, compared to China's 18.09%, and India's share of the chemistry literature was 5.34% in 2005 and 8.07% in 2014, compared to China's 15.64% in 2005 and 28.67% in 2014. Increasing volume of research notwithstanding, in the two years, i.e. 2013 and 2014, only 0.49% of chemistry papers from India (same as in the Elsevier report) found a place in the top one percentile of highly cited papers, compared to China's 1.19%. If we consider the top 10% of highly cited papers, India's share is 6.95% compared to China's share of 9.73%.

As seen from *InCites*, 3.4% of the world's S&T research output indexed in *Web of Science* (*WoS*) in 2014 was from India. This is meagre considering that India accounts for ~17% of the world's population. However, it matches with the country's nominal GDP of around 3% (as projected by IMF World Economic Outlook in April 2016). The share of chemistry papers from India in 2014 was 6.8%, double that for all of science. Indeed, of the 22 fields under which *Essential Science Indicators*, another Thomson Reuters database, classifies research output, chemistry accounts for the largest share of papers (19.7% in 2014) from India.

Data from *WoS–SCIE* (gathered on 1 August 2016) show that the three-year moving average of the number of chemistry papers from India increased steadily during the period 2007–2014 at a CAGR of 8.9%. However, chemistry papers classified under the subcategories biochemistry and molecular biology, and atomic, molecular and chemical physics grew faster – at a CAGR of 12.7% for the former and 13.4% for the latter.

Study by Arunan et al.

Arunan *et al.*[1] have pointed out that after years of stagnation, scientific research in India started looking up in the mid-1990s and by 2013 the country accounted for 3.5% of the world's research output, and with respect to chemistry, the growth was tangible and India rose to fifth place in the world in terms of the number of papers. The authors analysed the reasons for India's poor showing and offered several suggestions. According to them[1], there are only a few islands of excellence and around one half of India's chemistry research output comes from some 20 top-performing institutions. They have provided information on the proportion of papers with authors from Indian institutions in several prominent chemistry journals during the five years, i.e. 2007–2011: *Angew. Chem. Int. Ed.* (1.1%), *Phys. Chem. Chem. Phys.* (2.2%), *Org. Lett.* (2.5%), *Langmuir* (2.9%), *J. Phys. Chem. C* (3.8%), *J. Phys. Chem. A* (4.0%), *Inorg. Chem.* (5.0%), *J. Org. Chem.* (5.2%), *Dalton Trans.* (5.4%), *J. Phys. Chem. B* (6.5%) and *Cryst. Growth Des.* (7.0%). They thought that while these figures might look promising they are less than what they ought to have been, a sentiment they had expressed about the growth in research in chemistry in India up to the late 1970s. Notice that they have not considered *JACS*. Indian researchers have not published many papers in that journal, or other multidisciplinary chemistry journals like *Angew. Chem. Int. Ed.*

We searched *WoS–SCIE* for India's share (including papers written in collaboration with authors working in overseas laboratories) in the same set of journals during the four years, i.e. 2012–2015 and found that in each one of them India's share has increased considerably over the figures given by Arunan *et al.*[1]: *Angew. Chem. Int. Ed.* (world: 10,027 papers; India: 176 papers; India's share: 1.76%), *Phys. Chem. Chem. Phys.* (10,541; 624; 5.92%), *Org. Lett.* (6,535; 371; 5.68%), *Langmuir* (7,528; 277; 3.68%), *J. Phys. Chem. C* (13,249; 618; 4.7%), *J. Phys. Chem. A* (5,526; 258; 4.7%), *Inorg. Chem.* (6,162; 413; 6.7%), *J. Org. Chem.* (5,490; 447; 8.14%), *Dalton Trans.* (7914; 844; 10.66%), *J. Phys. Chem. B* (6,588; 551; 8.4%), and *Cryst. Growth Des.* (2,949; 334; 11.32%). Notice that in some of these reputed journals, India's share is above its own share of 6.8% in all of chemistry. Anecdotal evidence gathered from chemists attributes the improved performance to enhanced investments, setting up of Indian Institutes of Science Education and Research and new Indian Institutes of Technology, and increased enrollment of Ph D students. Several researchers consider that the morphing of the Science and Engineering Research Council into Science and Engineering Research Board has made a difference. However, no evaluation has been made so far.

India's contributions in the leading chemistry journals

As seen from *WoS–SCIE*, the journals most often used by Indian chemists in 2015 were *RSC Advances* (2,174 papers), *J. Alloys Compounds* (306), *Tetrahedron Lett.*

(289), *J. Indian Chem. Soc.* (283), *Dalton Trans.* (274), *Phys. Chem. Chem. Phys.* (263), *New J. Chem.* (240), *J. Mol. Struct.* (219), *Eur. J. Med. Chem.* (192), *Chem. Commun.* (197), and *Med. Chem. Res.* (168).

For our analysis of India's contribution to the literature of chemistry, we chose to look at the multi-disciplinary chemistry journals, which are highly regarded. In addition, we analysed papers published from India in a set of quality journals covering most chemistry specialties (Box 1).

Although *JACS* began publication in 1879, and *Angewandte Chemie* in 1887, no paper from India appeared in these journals for a long time. It took 24 years after Ray[9] sowed the seeds of modern chemistry in India with his first paper from the Indian soil for a paper by Dhar[10], from India to appear in *JACS*. During this period, Ray and his group had published 70 papers. From then on 696 papers from India have appeared in *JACS* till the end of 2015. Much of the data for papers from India in *JACS* were gathered manually, as the journal site does not provide for country search. We used full-text keyword search using 'India' as the search term and then scrutinized search results one by one to identify papers with 'India' in the byline. We did this to find out papers published up to 1972 and found 147 papers with an author from India. We found later papers with a *WoS–SCIE* search.

Box 1. Quality journals across all branches of chemistry considered to assess the rise in contributions from India

Accounts of Chemical Research
Angewandte Chemie International Edition
Biochemistry
Chemical Communications
Chemical Science
Crystal Growth & Design
Dalton Transactions
Electrochemical Communications
Electrochimica Acta
Inorganic Chemistry
Journal of Biological Chemistry
Journal of Catalysis
Journal of Chemical Physics
Journal of Organic Chemistry
Journal of Physical Chemistry A
Journal of Physical Chemistry B
Journal of Physical Chemistry Letters
Journal of the American Chemical Society
Journal of the American Society of Mass Spectrometry
Journal of the Electrochemical Society
Langmuir
Macromolecules
Nature
Nature Chemistry
Organic Letters
Polymer
Proceedings of the National Academy of Sciences of the United States of America
Science

The only Indian paper in *Angew. Chem.* (before it started appearing in English) was by Srikantan and Rengachari[11] from Andhra University and it appeared in 1937. The next paper in this journal from India appeared, as was the case for most countries, only after the International Edition commenced publication in 1962; it was by Palit[12]. The second Indian paper[13] appeared only in 1972, and since then 425 papers have appeared in *Angew. Chem. Int. Ed.* till the end of 2015.

Journal of the American Chemical Society

With a view to seeing the volume of work published from India in leading multidisciplinary chemistry journals in perspective, we present in Table 1 the number of papers published by scientists from a few Asian countries over the 25-year period, i.e. 1991–2015. The number of papers published in *JACS* by China and Singapore is growing much more rapidly than in other countries. The 495 papers published by Indian researchers in *JACS* during this period (Table 1) came from 82 institutions. The Indian institutions from where papers in *JACS* have often come in the 25 years (as seen from the byline) are: Indian Institute of Science (IISc, 107 papers), National Institute of Interdisciplinary Science and Technology (NIIST, 46), National Chemical Laboratory (NCL, 44), Indian Institute of Technology, Kanpur (IITK, 43), University of Hyderabad (UoH, 39), Indian Institute of Chemical Technology (IICT, 32), Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR, 31), Indian Association for the Cultivation of Science (IACS, 25), Indian Institute of Technology, Bombay (IITB, 24), Bhabha Atomic Research Centre (BARC, 17) and Indian Institute of Technology, Madras (IITM, 13). As collaboration has increasingly become the norm, there may be authors from more than one institution in many papers.

The Indian researchers who have published often in *JACS* in the 25 years are E. D. Jemmis (IISc, 25 papers), P. Balaram (IISc, 21), G. R. Desiraju (IISc, 16), A. Ajayaghosh (NIIST, 15) and D. Ranganathan (14). Restricting our attention to the recent past, we see some emerging Indian authors who have published often during 2011–2015. There were 144 papers with 691 author names in the byline, including many foreign authors. The emerging Indian researchers include Rahul Banerjee (NCL, 6) and Abhishek Dey (IACS, 5), Partha Sarathy Mukherjee (IISc, 4) and Sharath Kandambeth (4). All institutional affiliations may not be the ones from where an author might have written all his papers. For example, both Jemmis and Desiraju were working at UoH before they moved to IISc, and 18 of the 25 papers by Jemmis, and 12 of the 16 papers by Desiraju in *JACS* were from UoH. Also, it is not always easy to relate a paper to its correct author and affiliation, e.g. S. Roy could be Subendhu Roy (IISc, two papers in *JACS* during 2011–2015) or Sudipta Roy (IISER, Kolkata, three papers in *JACS*). Here we

Table 1. Number of papers published by selected Asian countries in three general chemistry journals during 1991–2015 (as seen from *Science Citation Index Expanded*)

Country	1991–2000		2001–2010		2011–2015		Total	
	No. of papers	Sum of citations	No. of papers	Sum of citations	No. of papers	Sum of citations	No. of papers	Sum of citations
JACS								
Japan	2,111	181,678	3,820	293,250	1,509	44,657	7,440	519,585
China	95	8,549	1,513	169,758	1,857	83,257	3,465	261,564
South Korea	135	13,660	649	65,910	485	19,198	1,269	98,768
Australia	269	18,726	363	26,545	225	7,550	857	52,821
India	138	9,029	213	14,948	144	4,206	495	28,183
Taiwan	97	7,158	263	18,622	128	3,928	488	29,708
Singapore	7	779	184	20,593	228	9,496	419	32,505
Total	2,852	239,579	7,005	609,626	4,576	172,292	14,433	1,023,134
World	22,229	1,697,637	30,981	2,364,429	14,428	442,825	67,638	4,504,891
Angew. Chem.								
Japan	479	37,814	1,771	129,574	1,292	28,646	3,542	195,356
China	48	5,246	1,049	113,757	2,210	75,134	3,307	193,536
South Korea	33	3,221	404	36,841	405	11,246	842	51,124
Australia	53	7,765	177	16,009	240	6,731	470	30,391
India	39	4,784	155	16,501	202	4,791	396	25,991
Singapore	9	735	109	10,298	269	9,019	387	20,008
Taiwan	19	867	109	7,251	135	3,529	263	11,612
Total	680	60,432	3,774	330,231	4,753	139,096	9,207	528,018
World	6,515	488,126	14,848	1,190,169	12,204	316,050	33,567	1,934,945
Chem. Commun.								
China	331	12,657	2,219	118,910	6,084	117,338	8,634	248,905
Japan	2,161	62,312	2,313	82,188	1,850	25,037	6,324	168,918
South Korea	137	5,895	662	33,236	946	15,517	1,745	54,648
India	377	11,653	462	17,678	794	11,347	1,633	40,678
Australia	352	10,931	361	16,416	470	7,809	1,183	35,156
Taiwan	164	4,210	232	9,653	312	5,131	708	18,994
Singapore	38	1,987	183	8,316	410	8,940	631	19,243
Total	3,560	109,645	6,432	286,397	10,866	191,119	20,858	586,542
World	11,887	378,785	15,831	652,149	17,520	276,443	45,238	13,07,377

JACS average cites per paper: world 66.6, India 56.93 and China 75.49. *Angew. Chem.* average cites per paper: world 57.64; India 65.63 and China 58.52. *Chem. Commun.* average cites per paper: world 28.9, India 24.9 and China 28.82.

advocate the universal adoption of ORCID (www.orcid.org) by scientists and scholars[14].

About 44% of Indian papers in *JACS* were written in collaboration with overseas authors. The overseas collaborators were mostly from the US, Germany, Japan, UK and France. At the institution level, most collaborative papers have been with authors from the US Department of Defense (17), US Navy (16), Naval Research Laboratory (15), CNRS, France (12), and US Department of Energy (9). Universities have contributed much less, prominent among them being the University of Gottingen and the University of California System (eight each), and the Universities of Oxford, Osaka and Stuttgart (six each).

Currently, 60% of papers are internationally co-authored as against a little less than 20% in 1992 (ref. 15). The 44% we have for the Indian papers during the 25-year period is to be expected.

Research published in *JACS* from other Asian countries also has a substantial component of overseas collaboration: China (>65%), Australia (57%), Singapore (54.9%), South Korea (48.6%), Taiwan (31.8%) and Japan (20.7%).

Papers from India in *JACS* have received on average 57 citations per paper as against 66.6 for the world and 75.5 for China.

During the 25 years, *JACS* had published 67,638 papers, of which 39,477 (58.4%) were from the US, 5156 (7.6%) from Germany, 3465 (5.1%) from China and 495 (0.7%) from India. Together these papers have been cited more than 4.5 million times; four of these papers have been cited more than 5000 times, seven more than 4500 times and 71 not less than 1000 times (till 12 May 2016).

Angewandte Chemie International Edition

Table 1 also presents the number of papers published by selected Asian countries in *Angew. Chem. Int. Ed.* It

reveals that Asia's share in the journal is increasing rapidly, and in particular, the increase in contribution from China and Singapore is striking. Encouraged by such rapid growth of chemical research in the region, Wiley-VCH, the publisher of *Angew. Chem. Int. Ed.*, partnered with the chemical societies in Asia (including the Chemical Research Society of India) and started two new journals, viz. *Chemistry – An Asian Journal*, and *Asian Journal of Organic Chemistry*[16].

The 396 papers published by Indian researchers in *Angew. Chem. Int. Ed.* during 1991–2015 (Table 1) came from 84 institutions. Prolific contributors from India include A. Ajayaghosh (NIIST, 18), G. R. Desiraju (IISc, 14), C. N. R. Rao (JNCASR, 13), and S. J. George (JNCASR, 11). In the five years, i.e. 2011–2015, there were 202 papers with 729 author names in the byline, including many foreign authors. The emerging Indian researchers who have published often in these five years include Debabrata Maiti (IITB 6), Kana M. Sureshan (NIIST, 5), Ashwini K. Phukan (University of Tezpur, 5), Tapan Kanti Paine (IACS, 5), Suhrit Ghosh (IACS, 4), Narayan Pradhan (IACS, 4), Talappil Pradeep (IITM, 4), Upadrasta Ramamurty (IISc, 4), Govindasamy Mugesh (IISc, 4) and Venkataramanarao G. Anand (IISER Pune, 4).

About 38% of papers was written in collaboration with overseas authors. The overseas collaborators were mostly from Germany, USA, UK, Japan and France. At the institution level, most collaborative papers have been written with authors from the University of Gottingen (11), CNRS, France (10), University of Stuttgart (7), University of Wurzburg, University of Duisburg Essen and Max Planck Society (six each) and University of Cambridge (5).

Research published in *Angew. Chem. Int. Ed.* from other Asian countries also has a substantial component of overseas collaboration: Australia (58.7%), Singapore (46.3%), South Korea (40.3%), China (34.3%), Taiwan (33.1%) and Japan (18.7%). Papers published in *Angew. Chem. Int. Ed.* from India are cited on average 65.6 times, which is greater than the world average of 57.6 and China's average of 58.5.

During this period *Angew. Chem. Int. Ed.* had published 33,567 papers, of which 9,395 (28%) were from Germany, 8,489 (25.3%) from USA, 3,307 (9.9%) from China and 396 (1.2%) from India. Together these papers have been cited 1.16 million times: 4 of them more than 5000 times, 9 more than 3000 times, 89 more than 1000 times and 4687 not less than 100 times till 12 May 2016.

Chemical Communications

While India has recorded modest increase in the number of papers published in *Chem. Commun.*, the growth in the contributions from China, South Korea and Singapore is indeed dramatic (Table 1). Indian chemists from 178 institutions have published 1633 papers, the number growing from 15 in 1985 to 197 in 2015. Unlike with *JACS* and *Angew. Chem.*, there has been a rapid rise in papers from India since 2008 (Figure 1). What could be the reason? Many users are happy with the urgent and high-quality communications; the communications are most recent, short and to the point. Also, says a long-time user of the journal, 'it lets me say exactly what I want to say', especially when one is working on a very interpretative subject and has to sell an idea rather than data. The other prestigious journals could be intrusive in that the referees could be over-cautious to the point of interfering with an author's idea. Some older chemists think that perhaps because of the sudden growth in the number of papers published there may be a few which may not measure up to the standards maintained till a few years ago.

The 1,633 papers from India have been cited on an average about 25 times compared to about 29 for both China and the world. About 350 Indian papers (21%) have in the byline at least one author with an overseas address. These collaborating authors hail from, among other countries, USA (76), Germany (48), UK (46), Japan (34) and France (30). Six institutions account for more than 50% of all papers from India in this journal: NCL (204), IISc (202), IACS (139), UoH (127), IICT (109) and IITB (76). Outside of the list of prominent centres of chemical research, we also find a state university, viz. Guru Nanak Dev University, contributing 19 papers to this journal. Collaborating overseas institutions include CNRS, France (20), National Institute of Materials Science, Japan (10), University of California System (8), Japan Science and Technology Agency (8), and Howard University (8).

Table 2 shows India's participation in all three journals – *JACS*, *Angew. Chem.* and *Chem. Commun.* Only 35 Indian institutions have published papers in all three. Only nine institutions have published at least 100 papers in all three journals put together in the 25 years: IISc

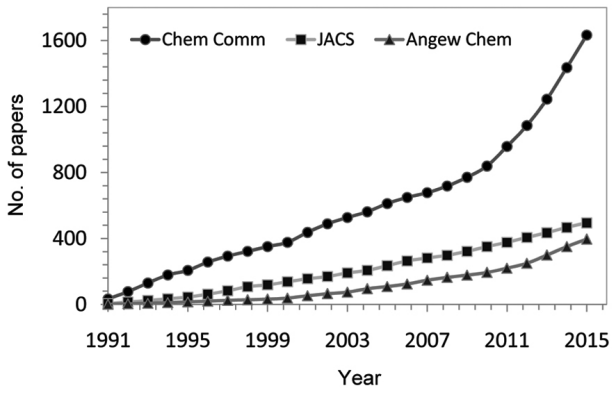

Figure 1. Number of papers published from India in three major general chemistry journals.

Table 2. Distribution of papers published in all three general chemistry journals during 1991–2015 by institution

Institution	*JACS*		*Angew. Chem.*		*Chem. Commun.*		Total	
	No. of papers	Sum of citations	No. of papers	Sum of citations	No. of papers	Sum of citations	No. of papers	Sum of citations
IISc, Benglauru	107	5,779	64	4,603	202	6,280	373	16,662
CSIR-NCL, Pune	44	2,398	37	1,660	204	4,615	285	8,673
University of Hyderabad, Hyderabad	39	3,180	28	5,283	127	5,679	194	14,142
IACS, Kolkata	25	819	28	793	139	3,548	192	5,160
CSIR-IICT, Hyderabad	32	2,676	25	1,537	109	2,510	166	6,723
IIT Kanpur	43	2,571	25	1,433	73	1,507	141	5,511
JNCASR, Bengaluru	31	1,930	31	3,369	66	3,597	128	8,896
IIT Bombay, Mumbai	24	1,234	24	1,055	76	1,350	124	3,639
CSIR-NIIST, Thiruvananthapuram	46	3,997	24	2,687	44	992	114	7,676
IIT Madras, Chennai	13	382	12	471	56	918	81	1,771
IIT Kharagpur	11	730	6	95	57	1,887	74	2,712
IISER, Pune	5	98	9	407	53	683	67	1,188
CSIR-CSMCRI, Bhavnagar	7	545	5	236	40	986	52	1,767
Bhabha Atomic Research Centre, Mumbai	17	1,016	8	765	23	421	48	2,202
IISER, Kolkata	7	52	5	196	33	543	45	791
Guru Nanak Dev University, Amritsar	2	51	1	11	38	736	41	798
IIT Guwahati	3	51	9	425	28	688	40	1,164
IISER, Thiruvananthapuram	12	216	11	169	9	89	32	474
University of Delhi, Delhi	2	255	3	244	23	564	28	1,063
CSIR-CDRI, Lucknow	5	247	8	162	13	214	26	623
Jadavpur University, Kolkata	3	340	4	228	19	537	26	1,105
IISER, Bhopal	1	12	3	30	17	295	21	337
TIFR, Mumbai	5	103	5	137	11	80	21	320
University of Pune, Pune	7	214	2	47	12	157	21	418
Panjab University, Chandigarh	4	151	2	283	10	83	16	517
University of Calcutta, Kolkata	2	41	2	10	12	133	16	184
CSIR-IICB, Kolkata	1	28	2	14	10	75	13	117
NIPER, Mohali	2	137	1	27	10	365	13	529
CSIR-CCMB, Hyderabad	5	215	1	37	5	124	11	376
CSIR-IGIB, New Delhi	3	76	3	107	4	28	10	211
Tezpur University, Tezpur	1	28	7	77	2	15	10	120
CSIR-CLRI, Chennai	4	123	4	117	1	17	9	257
CSIR-NPL, New Delhi	4	457	1	4	2	11	7	472
BB Ambedkar University, Lucknow	1	14	2	40	3	60	6	114
S.N. Bose National Centre for Basic Sciences, Kolkata	1	16	3	110	1	5	5	131

(373), NCL (285), UoH (194), IACS (192), IICT (166), IITK (141), JNCASR (128), IITB (124) and NIIST (114). Here the affiliations given are those found in the byline. Not all institutions have been in existence from 1991. For example, the IISERs, Tezpur University, and B. R. Ambedkar University were established after 1991. As pointed out by Arunan *et al.*[1], only a few institutions publish in high-quality journals and that too only a few papers[1]. In this context, it is heartening to see a few not-so-prominent institutions in this list.

Accounts of Chemical Research

During 1991–2015, *Acc. Chem. Res.* had published 3,497 papers (cites per paper (CPP) 127.15), of which India's share was 72 papers (CPP 157.39) and China's was 299 papers (CPP 107.14). Among the 72 papers from India, 25 have received more than 100 citations and 3 of them more than 1000. The institutions and researchers who are responsible for such high average citations are UoH, JNCASR, NIIST and IISc, and Desiraju, Rao, Nair and Ajayaghosh.

We also looked at publications from India in two journals which commenced publication in the past decade.

Nature Chemistry

Since its beginning in 2009 till the end of 2015, *Nature Chem.* has published 1621 papers at a CPP of 45.26. Of these, India's share is 11 papers (CPP 23.45) compared to China's 57 papers (CPP 66.82).

Chemical Science

Although this journal commenced publication in 2010, it was only in 2014 that India accounted for more than

10 papers. Up to the end of 2015, Indian scientists had published 28 papers (CPP 13.89) compared with China's 591 papers (CPP 22.69). These papers have come from, among others, NCL, JNCASR, NIIST and IISER-Kolkata.

Multidisciplinary journals

Chemists use, apart from mainstream chemistry journals, multidisciplinary journals as well to publish their work. Notable among them are *Nature*, *Science* and *PNAS*. A *WoS–SCIE* search for India's contribution to *Nature* during 2010–2015 showed 80 records. If we leave out general news stories, policy-related notes, book reviews, etc., the number of original research contributions in chemistry reduces to two – one each under materials chemistry and biochemistry. A search of *Science* showed 92 publications from India in the six years, i.e. 2010–2015, of which six are original research papers in chemistry – four articles, one editorial material and one review. A search of the chemistry section of the website of *PNAS* showed that 12 papers have an author affiliation in India. Clearly, Indian chemists do not publish in these journals often.

Highly cited papers

Many chemists prefer to publish in high-impact specialty journals. A search of *WoS–SCIE* revealed that 1.29% of the world's more than 1.18 million chemistry papers published during the six years, 2009–2014 have been cited at least 100 times. The corresponding figures for China are 1.65%, of more than 240,000 papers. A little over 0.5% of papers from India (388 out of 68,300 papers) also won 100 or more citations by the end of September 2016. These 388 papers have appeared in 103 journals, including *J. Phys. Chem. C* (15 papers from India during 2009–2014), *Colloids and Surfaces B* (15 papers) and *Org. Lett.* (12 papers). Publishing steadily and profusely in specialty journals of class may help young Indian chemists emerge as opinion makers.

International collaboration

Data on publications from India in journals classified under the *WoS–SCIE* categories 'Chemistry' and 'Electrochemistry' show that the share of internationally co-authored papers from India increased from 15.4% in 2005 to 20.7% in 2014 for a CAGR of 3.34%. The number of countries with which India collaborated increased steadily during this period: 56 in 2005; 65 in 2008; 75 in 2011 and 95 in 2014.

Of the 97,913 chemistry papers published from India during this 10-year period, 979 (1%) have been cited at least 100 times (as on 2 August 2016). Of these, 276 were written by authors in Indian laboratories in collaboration with at least one author from one of 40 countries. Thus a little over 28% of the highly cited papers were internationally co-authored. In general, papers resulting from international collaboration tend to be cited more often than entirely domestically generated papers.

Discussion

Nature Index has focused on projecting a positive image of science in India today and has given hope that the perception that India is not producing anything of value will be dispelled. Referring to the progress being made in research in India, the Minister for Science and Technology, Harsh Vardhan made a special mention of the growth achieved in chemistry and nanoscience[17].

Nature Index tracks chemistry research published in only 18 journals. In contrast *SCImago*, powered by Scopus, tracks papers in 857 journals, and *WoS–SCIE* covers 600 journals publishing papers in chemistry; of these, Indian researchers have used 468 in 2014. *SCImago* and the Elsevier report to DST (both based on Scopus data) and the Thomson Reuters report to DST based on *WoS–SCIE* data place India in the third position in chemistry research after China and USA, compared to eighth by Nature Index. As the number of journals analysed increases by an order of magnitude, more papers from India get in taking it to a higher rank, and when publications in only high quality journals are considered, India's rank falls leading to the question 'are we publishing mediocre stuff'?

If we expand the scientific enterprise, will it lead to excellence? 'Every quality manifests itself in a certain quantity, and without quantity there can be no quality' is one of Chairman Mao's oft quoted sayings. After a visit to Israel, Feng[18] concluded that 'when you have many, then "quantum fluctuation" will allow a few to jump out of the system to be recognized by this world'. Many researchers in India have emphasized the need to expand the base[19,20], which is easier said than done. As pointed out by Vale and Dell[21], 'India's greatest challenge will be in educating, recruiting, and supporting its next generation of scientists', but 'the brightest students in India are simply not coming to graduate school'.

To verify the premise that a large increase in the number of researchers and research papers will increase the number of better-quality papers, we checked from *WoS–SCIE* the number of papers published from India in a set of quality journals covering most specialties (Box 1) over six years, and calculated CAGR. We found that the number of papers from India in the selected set of journals rose from 1064 in 2010 to 1742 in 2015 (CAGR of 10.4%). During the same period, the overall number of papers published in chemistry recorded a CAGR of 7.1%. Although chemistry research in India is doing better in

recent years than before, as evidenced by an increase in the number of papers published overall and the number of papers in high-quality journals, papers from India do not find a place in hot research fronts[22]. Also, as seen from the DST-commissioned Thomson Reuters report[8], India's percentage of highly cited papers in chemistry was below the world average right from 2005 to 2014 and below that of most advanced and emerging economies and the increase in better-quality publications was not enough to take India into the top four countries with the largest number of 10% of most-cited publications in chemistry in 2003–2012 (ref. 23). In chemistry, USA, China, Germany and Japan lead in the number of highly cited papers.

China has recorded a phenomenal rise in the number of highly cited papers along with the rise in the number of published research papers[24]. As shown in Figure 2, China started with a meagre lead over India in the number of papers in the top one percentile of the most highly cited papers in 2000 and by 2014, the lead increased by an order of magnitude. Indeed, China overtook the traditional leader USA in the number of most highly cited one percentile of papers in 2013. As OECD's STI Scoreboard for 2015 shows, China is in the top four countries with the largest number of 10% most-cited publications in 11 fields (among 27 fields)[23]. In contrast, India figures in only one field, viz. chemical engineering.

Of the 35 Indian institutions that have published at least one paper each in *JACS*, *Angew. Chem.* and *Chem. Commun.* in the 25 years, i.e. 1991–2015, 21 are higher educational institutions, including four state universities (Jadavpur, Pune, Calcutta and Panjab), 10 CSIR laboratories, 2 DST laboratories and 2 DAE institutions. Many of these papers are written in collaboration with overseas researchers: 44% of papers in *JACS*, 38% in *Angew. Chem.* and 21% in *Chem. Commun.* A large number of these papers come from nine institutions led by IISc and NCL. That only a few higher educational institutions and even fewer state universities figure is a matter for concern.

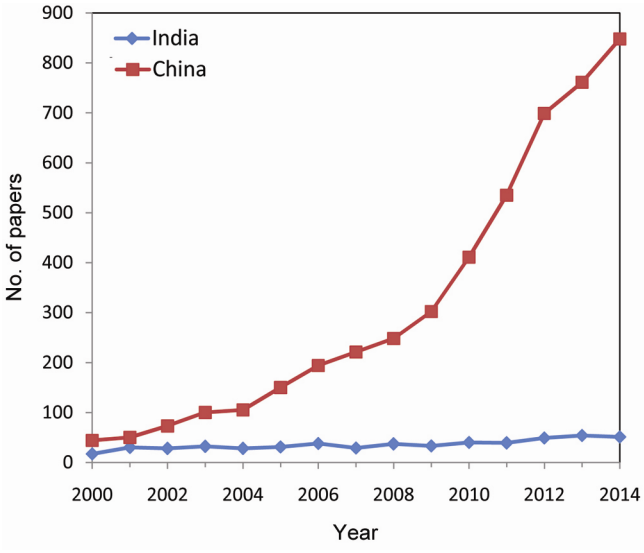

Figure 2. Number of papers from India and China in the top one percentile of the most highly cited chemistry papers as seen from the Web of Science.

One reason Indian researchers have not published many papers in *JACS* is the same as why they have not published many papers in *Nature* and *Science*. These are not only multidisciplinary (*JACS* catering to all subfields of chemistry), but also expect papers to straddle disciplinary boundaries. Unfortunately, most academic departments have not broadened their scope encompassing emerging areas of chemical biology and materials science, nor have they come out of their puritanical tradition of keeping separate physical, organic and inorganic chemistry[25,26]. More importantly, Indian laboratories are not nimble in taking advantage of the techniques that are transforming chemical research dramatically in the West. What is more, India has failed to take advantage of its traditional strengths such as natural products chemistry and inorganic chemistry[25].

It is also of concern that there was not a single Indian chemist (working in an Indian institution) in the list of the world's top 100 chemists prepared by Thomson Reuters based on impact of their research published over the 11 years, i.e. 2000–2010, whereas there were three from South Korea and one each from Brazil and South Africa[27]. On the brighter side, there are individuals with some promise working in lesser known institutions who could do better with some support. It is imperative that we increase the number of researchers as well as students at all levels and improve the quality of teaching. Ganesh[28] and Arunan *et al.*[1] believe that Indian science will benefit substantially if we hire international faculty.

In the recent past, the Government has established several fellowships aimed at 'reversing the brain drain from the country' and getting back the scientific minds that have gone away. However, these efforts are yet to bear fruit, while similar efforts have been successful in China (K. S. Jayaraman, pers. commun.). Currently, students graduating from better-known institutions prefer to go abroad for higher studies. According to Ganesh[28], more than 60% of IISER graduates leave the country for graduate studies, as was predicted by Desiraju[29] in 2008. On the other hand, not all Ph Ds even from the best of Indian institutions find research and teaching assignments, mentions a concerned professor at one of India's top institutions.

1. Arunan, E., Brakaspathy, R., Desiraju, G. R. and Sivaram, S., Chemistry in India: unlocking the potential. *Angew. Chem. Int. Ed.*, 2013, **52**, 114–117; doi:10.1002/anie.201206960.
2. Kogleck, L., Priyadarshini, S., Pincock, S., Bocquet, A. and Gilloch, C., *Indian Science Ascending – A Nature Index Analysis*, Springer Nature, 2015; https://www.natureindex.com/pdf/news/indian-science-ascending.pdf (accessed on 5 August 2016).
3. Phillips, N., Rising stars. *Nature*, 2016, **535**, S49; doi:10.1038/535S49a.

4. Nature Index, 2013 tables: countries – chemistry; http://www.natureindex.com/annual-tables/2013/country/chemistry (accessed on 5 August 2016).
5. Nature Index, 2016 tables: countries – chemistry; http://www.natureindex.com/annual-tables/2016/country/chemistry (accessed on 5 August 2016).
6. Huggett, S., Gurney, T. and Jumelet, A., International comparative performance of India's research base (2009–14): a bibliometric analysis by Elsevier. Department of Science and Technology (DST), India, 2016; http://nstmis-dst.org/PDF/Elsevier.pdf (accessed on 5 August 2016).
7. Huggett, S., Gurney, T. and Jumelet, A., International comparative performance of India's research base (2009–14): a bibliometric analysis by Elsevier, DST, India, 2015.
8. India's research output and collaboration (2005–14): a bibliometric study (phase-II), by Thomson Reuters, DST, India, 2015; http://nstmis-dst.org/PDF/Thomson.pdf (accessed on 5 August 2016).
9. Ray, P. C., On the conjugated sulphates of the copper–magnesium group, *Proc. R. Soc Edinburg*, 1889, **15**, 267–283; doi:10.1017/S0370164600005502.
10. Dhar, N., Dissociation constant of weak acids and bases from solubility data. *J. Am. Chem. Soc.*, 1913, **35**, 800–802; doi: 10.1021/ja02195a019.
11. Srikantan, B. S. and Rengachari, S., Verwertung von Unkraut, I. Vergasung der Feigendistel (Opuntia Dillinii), *Angew. Chem.*, 1937, **50**, 249–250; doi:10.1002/ange.19370501304.
12. Palit, S. R., End group estimation in polymer compounds using dyes. *Angew. Chem. Int. Ed.*, 1962, **1**, 603; doi: 10.1002/anie.196206031.
13. Wiberg, N., Vasisht, S. K. and Fischer, G., Bis(trimethylgermyl) diimine. *Angew. Chem. Int. Ed.*, 1976, **15**, 236–237; doi:10.1002/anie.197602361.
14. Arunachalam, S. and Madhan, M., Adopting ORCID as a unique identifier will benefit all involved in scholarly communication. *Natl. Med. J. India*, 2016, **29**(4), 227–234.
15. *Science* (journal): history; http://america.pink/science-journal_3946247.html (accessed on 5 August 2016).
16. Interview with Dr Peter Goelitz, Editor-in-chief of *Angewandte Chemie*, *CHEMCOS*, 2014; http://chemistry.iitd.ac.in/chemcos/chemcos/present%20issue/9%20Personalities.pdf (accessed on 5 August 2016).
17. India's performance in research is impressive in recent years says Dr Harsh Vardhan, Minister for Science & Technology and Earth Sciences, Press Information Bureau, Ministry of Science & Technology, Government of India, 2016; http://pib.nic.in/newsite/PrintRelease.aspx?relid=137602 (accessed on 5 August 2016).
18. Feng, D. H., Opening comment to 2007–2009 Taiwan – Israel Joint Final Report Workshop, *Huaren E-Magazine*, 2009; http://www.huaren.org/Text/uploadedFiles/1259274908902-8521.pdf (accessed on 5 August 2016).
19. Balaram, P., Rankings and records. *Curr. Sci.*, 2003, **84**, 1279–1280; http://www.iisc.ernet.in/currsci/may252003/1279.pdf (accessed on 5 August 2016).
20. Desiraju, G. R., Science in a changing world. *Angew. Chem. Int. Ed.*, 2011, **50**, 5590–5591; doi:10.1002/anie.201102495.
21. Vale, R. D. and Dell, K., Aiming high for the future. *J. Cell Biol.*, 2009, **184**, 342–353; doi: 10.1083/jcb.200812123.
22. Research fronts 2014: 100 top ranked specialties in the sciences and social sciences. The National Science Library, Chinese Academy of Sciences and Thomson Reuters IP & Science, 2014; http://sciencewatch.com/sites/sw/files/sw-article/media/research-fronts-2014.pdf (accessed on 5 August 2016).
23. Science and research today: highlights of the OECD science, technology and industry scoreboard. OECD, 2015; http://www.oecd-org/sti/Science-brief-scoreboard.pdf (accessed on 5 August 2016).
24. Van Noorden, R., China by the numbers: research capacity has grown rapidly, and now quality is on the rise. *Nature*, 2016, **534**, 452–453; http://www.nature.com/news/china-by-the-numbers-1.20122 (accessed on 5 August 2016).
25. Balaram, P., Chemists and chemistry, *Curr. Sci.*, 2011, **100**, 5–6; http://www.currentscience.ac.in/Volumes/100/01/0005.pdf (accessed on 1 September 2016).
26. Balaram, P., Where has chemistry gone? *Curr. Sci.*, 2000, **79**, 927–928.
27. Top 100 chemists, 2000–2010: special report on high-impact chemists, *Science Watch*, 2011; http://archive.sciencewatch.com/dr/sci/misc/Top100Chemists2000-10/ (accessed on 5 August 2016).
28. Ganesh, K. N., Connect research with education. *Nature*, 2015, **521**, 154; http://www.nature.com/news/research-management-priorities-for-science-in-india-1.17509#/ganesh (accessed on 5 August 2016).
29. Desiraju, G. R., Science education and research in India, *Econ. Polit. Wkly*, 2008, **43**, 37–43; http://www.jstor.org/stable/40277564 (accessed on 1 September 2016).

ACKNOWLEDGEMENT. We thank Prof. T. A. Abinandanan, Indian Institute of Science, Bengaluru for useful discussions, and the three referees for their valuable suggestions.

Received 5 September 2016; revised accepted 11 October 2016

doi: 10.18520/cs/v112/i07/1330-1339